Department of Physics
UNIVERSITY OF NEW HAMPSHIRE
Durham

MEV PARTICLES IN THE OUTER ZONE: EXPLORER 12

Richard L. Kaufmann
Department of Physics
University of New Hampshire
Durham, New Hampshire 03824

and

Andrei Konradi
Goddard Space Flight Center
Greenbelt, Maryland 20771

FEBRUARY 1969

ABSTRACT

Fluxes of 100-kev electrons and protons on high L-shells are compared with fluxes of more energetic particles in the heart of the outer zone. A number of characteristics of the changes in these fluxes are noted and compared with predictions of several models of particle acceleration and energy transport. It is concluded that two separate mechanisms are required to produce Mev protons in the heart of the outer zone. Protons must first be accelerated to several hundred kilovolts on or above the highest closed drift shells. Several pumping mechanisms which can do this are discussed. Diffusion in which the first adiabatic invariant is conserved can then transport these protons to the heart of the outer zone and further accelerate them to the Mev energy range. A convection system and its associated electric fields contain enough energy to drive the diffusion. Electrons can undergo a similar acceleration process. In addition, some electrons which originally mirror near the neutral sheet can be accelerated from 10 kev directly to the Mev range in a single step. Electrons also undergo a rapid form of diffusion in which the first adiabatic invariant is violated. Finally, resonant interactions with waves near the equator in the heart of the outer zone could locally accelerate some particles to 1 Mev.

1. INTRODUCTION

Data from the Explorer 12 ion and electron detector (Davis and Williamson, 1963) are presented in Section 2. Explorer 12 had a highly elliptic orbit with apogee of 13.1 earth radii. Local time at apogee varied from 13:00 to 05:00. A comparison is made between fluxes of 100-kev particles on high L-shells and fluxes of roughly 1-Mev particles in the heart of the outer zone.

To produce the observed Mev particles in the heart of the outer zone, energy must both be transferred to individual charged particles and transported across field lines. A number of energy transfer (acceleration) and transport mechanisms are discussed in Section 3.

In Section 4 the data are compared to predictions of the proposed mechanisms. The data are consistent with a model in which third invariant diffusion, driven by a fluctuating electric field or convection system, provides the primary energy transport mechanism. Acceleration takes place during the diffusion process and also on high L-shells. The data are also consistent with a model in which low energy particles transport energy to the heart of the outer zone. Acceleration to 1 Mev must then take place locally on these lower L-shells.

2. DATA PRESENTATION

Data from all inbound orbits between August 16, 1961 and October 10, 1961 are presented in Figure 1. Inbound orbits were selected because they took place nearest the geomagnetic equator. The first two weeks of Explorer 12's lifetime were farily quiet, as was the week preceding launch. The first significant event was the sudden commencement of a moderately severe magnetic storm on August 29. K_p reached a maximum of 6, AE exceeded 1100 gammas (Wong et al., 1967), and Dst decreased by about 50 gammas. No other major event occurred until 26 days later when, on September 24, a very similar storm took place. K_p again reached a maximum of 6, AE exceeded 900 gammas, and Dst again decreased by about 50 gammas. These two storms exhibit a number of common properties and will be referred to as the pair of recurrent storms. Similar changes in K_p and Dst also appeared at the same phase of the two preceding solar rotations.

Six days after the second recurrent storm, the first major geomagnetic storm began. K_p reached 9, AE exceeded 1500 gammas, and Dst decreased by 150 gammas. By the end of the period covered in Figure 1, conditions had nearly recovered from this event.

A number of studies have been carried out to investigate Kellogg's (1959) suggestion that energetic particles move from a source on a high L-shell to the heart of the outer zone

via breakdown of the third adiabatic invariant. To test this third invariant diffusion mechanism we can look for a source of particles near the magnetopause and for a perturbation which supplies energy to drive the diffusion. Two curves showing peak directional fluxes of electrons with energies above about 100 kev are included in Figure 1. The curve labeled "100-kev electrons near magnetopause" is the flux of electrons seen one hour after the satellite has entered the magnetosphere. A time interval of one hour was selected because fluxes of 100-kev electrons generally increase rapidly just inside the magnetopause, and reach a relatively stable level in less than one hour (Frank et al., 1966).

A clear correlation is evident between the flux of 100-kev electrons near the magnetopause and the magnetopause location. Linear regression analysis yields a correlation coefficient of -0.63 at zero lag as compared to about ± 0.2 at non-zero lags. This indicates that the flux of 100-kev electrons near the magnetopause increases whenever the magnetosphere is compressed, and is therefore not a good indicator of newly injected energetic electrons. The flux of 100-kev electrons at L = 8 is also included in Figure 1, and this flux is not nearly so well correlated with magnetopause location. The 100-kev electron flux at L = 8 rises to nearly identical levels during the two recurrent storms, and appears to provide a better indication of the presence of newly injected electrons. Note that both 100-kev electron curves reached as high

a level during the moderately disturbed period roughly midway between the recurrent storms as during the storms. In addition, more 100-kev electrons were injected on high L-shells after the moderate-sized recurrent storms than after the large storm of September 30.

Above the 100-kev electron curves in Figure 1 is a contour plot of the omnidirectional flux of electrons with energies exceeding about 1 to 2 Mev in the range $2 < L < 8$. The heavy line and slanted numbers indicate the location and magnitude of the peak flux. The threshold of this detector, which was used as a background monitor, has not been accurately determined.

An electron gains energy as it moves inward if its first adiabatic invariant is conserved. Its energy changes so that $(\gamma^2 - 1)/B_m$ = constant, where γ is the relativistic mass ratio and B_m is the mirror point field strength. Typical field strengths are about 100, 275, and 1000 gammas at $L = 8$, 5, and 3. Therefore, an equatorially mirroring electron would require a kinetic energy of 170 to 420 kev at $L = 8$ if it is to reach 1 to 2 Mev at $L = 3$, and 490 kev to 1.1 Mev at $L = 8$ if it is to reach 1 to 2 Mev at $L = 5$. The 100-kev electrons measured are not energetic enough to produce the 1- to 2- Mev detector response in the heart of the outer zone. However, since no data at intermediate energies are available, the "100-kev electrons at $L = 8$" curve will be used as the best available estimate of the source strength for a third invariant

diffusion mechanism.

The 1-to 2-Mev electron contour plot should be considered along with the array of numbers just above it. The numbers are values of B/B_o, the local field strength divided by the equatorial field strength, as computed from Jensen and Cain's (1962) field model. In the blank regions of this array, B/B_o is less than 2. The 1- to 2- Mev electron fluxes are weakly correlated with B/B_o in the heart of the outer zone, as has been noted by McIlwain (1966) and by Owens and Frank (1968). To illustrate this effect, data covering the decay of electrons injected during the first recurrent storm were subjected to a multiparameter least squares fit (Daniels, 1966). The fit indicated correlation at better than a 95% confidence level and suggested that these data in the heart of the outer zone could be normalized to $B/B_o = 1$ by introducing normalization factors of 3 or less.

The least squares fit also exhibited a correlation between the electron flux and Dst, as noted by McIlwain (1966). The significance of the correlation is high in the lower portion of the outer zone. The magnitude of the Dst dependence and the significance of a real correlation decrease with increasing L and the fit is no longer significant at a 95% confidence level at L = 5. The magnitude of the modification required to normalize the data to Dst = 0 is a factor of 3 for the data analyzed between the recurrent storms. Much larger modifications may be required for several days after a large

geomagnetic storm.

Finally, if the 1- to 2- Mev flux contours in Figure 1 are to be interpreted as the fluxes of electrons above some fixed threshold, then data must also be modified to account for changes in the electron energy spectrum. The ion and electron detector provides no reliable estimate of the spectrum near 1 to 2 Mev. Owens and Frank (1968) investigated this effect in this energy range and concluded the spectral effect is small relative to the B/B_o effect except during the initial stages of a geomagnetic storm.

The gross changes in electron contours in Figure 1 are not associated with any of the above effects. The three 1 to 2 order of magnitude flux increases are clearly associated with the August 29, September 24, and September 30 geomagnetic storms. Minor perturbations such as the more rapid than usual flux decrease from September 11 to 13 can be partly attributed to the B/B_o effect. The Dst effect is at least partly responsible for the slowness of the flux increase following the September 30 storm.

The two recurrent storms resulted in the injection of very similar fluxes of 1- to 2- Mev electrons with peak intensities at $L = 4.5$ in each case. The large September 30 storm first produced a sudden disappearance of the high energy electrons which were present near $L = 4.5$ as the storm began. Then a smaller flux of electrons was injected at $L = 3.5$. The magnitude of the injected flux may be related to the relatively

small flux of 100-kev electrons seen at L = 8 during the large storm. The injection altitude is closely related to the change in Dst during the storm. This effect has been previously noted (Williams et al., 1968) and will become more evident when more storms are discussed. Finally, no injection of 1- to 2-Mev electrons is associated with the high 100-kev electron fluxes at L = 8 midway between the recurrent storms. This illustrates the lack of a one- to-one correspondence between acceleration of "source" electrons at high L-values and the injection of more energetic electrons in the heart of the outer zone.

If third invariant diffusion is important it should affect all energetic particles simultaneously on a given L-shell provided the energetic particles have equal drift periods. For this reason, it is of interest to compare the 1- to 2- Mev electron flux contours to the similar flux map for 470-kev protons shown in Figure 1. One- and two- Mev electrons have drift periods 30% and 60% shorter than 470-kev protons in a dipole field, but this difference alone is unlikely to produce gross differences between the electron and proton flux contours.

Gross differences between the flux contours are produced by properties of the detector and by loss mechanisms. The proton detector is saturated within the 1000 flux curve so that even large changes in this region could not be observed. A comparison of electron and proton curves illustrates

the frequently noted fact that proton lifetimes are much longer than electron lifetimes. In fact, no significant long term decay of protons at the heart of the outer zone can be discerned from the data as presented in Figure 1.

The most pronounced feature of the proton contours is the strong B/B_o dependence in the heart of the outer proton zone. A strong B/B_o dependence indicates a strong concentration of protons in the equatorial plane. The difference between equatorial concentrations of electrons and protons may easily be produced by loss rather than by source mechanisms. Even if both groups of particles are produced by the same source, the short lifetimes of electrons suggest they cannot remain concentrated near the equator. Williams et al. (1968) have noted that 1-Mev electron mirror points are altered rapidly enough so that an equilibrium distribution is established in a flux tube even down to very high values of B/B_o within a few days. The much longer proton lifetimes suggest that the equilibrium distribution along a field line will differ from the electron equilibrium distribution, and that protons may never even reach an equilibrium between injection events.

The uppermost curve in Figure 1 is the peak directional flux of 100-kev protons at L = 8. These particles are considered as a possible source for the 470-kev protons at lower altitudes. Since the observed protons are non-relativistic, their energies change in proportion to the magnetic field

strength at their mirror points if the first adiabatic invariant is conserved. A 100-kev proton mirroring near the equator at L = 8 where the field strength is about 100γ would therefore have about 500 kev of kinetic energy at L = 4. The only significant peaks on this curve are associated with the previously noted storm events.

Figure 2 contains data for the period October 11, 1961 to December 5, 1961. The two curves involving the magnetopause are not included in Figure 2 because the satellite apogee was frequently below the magnetopause during this time interval.

One important new feature was observed in the 1- to 2- Mev electron contours during mid-October. The electron peak injected on September 30 was observed on the first two passes on Figure 2. Then there was a data gap while Dst decreased by 40 gammas. When data coverage resumed on October 15, two peaks were observed. The peak at L = 3.5 presumably represents the smooth decay of electrons injected during the September 30 storm. The peak at L = 5 would then represent additional electrons injected during the moderately disturbed period between October 12 and 15. The latter injection did not appear to disturb the previously injected electrons on lower field lines. This is in contrast to the complete disappearance of electrons at L = 4.5 noted on September 30 as new electrons were injected at L = 3.5.

The double peaked electron structure was observed

whenever data coverage was complete until the large disturbances began on October 26. A very large storm took place on October 28 as K_p reached 9 and Dst exceeded -250 gammas. Immediately after this storm, electrons peaked at L = 3.0, the lowest altitude observed during Explorer 12's lifetime. A double peaked structure was seen once more on November 8 to 9. This indicates that a small injection of electrons at L = 4.5 accompanied the disturbance on November 7 to 8, while the electrons injected by the large October 28 storm remained trapped.

An examination of 1- to 2- Mev electron data in Figures 1 and 2 illustrates the correlation between the altitude of peak fluxes and Dst. Most injection events involved Dst decreases of 40 to 100 gammas and peak electron fluxes between L = 4 and 5. On December 1, October 1, and October 28, Dst reached -124, -169, and -266 gammas. The corresponding L-shells at which peak fluxes were observed were about 4.0, 3.5, and 3.0.

3. ENERGY TRANSFER AND TRANSPORT MECHANISMS

Two problems are involved in the injection of electrons and protons with energies above 1 Mev into the heart of the outer zone. Assuming the solar wind is the basic energy source, some process must transfer one Mev of energy to a single particle. In addition, this energy must be transported to the heart of the outer zone. In this section,

mechanisms will be classified according to the region of space in which an individual particle's energy reaches 1 Mev.

Local acceleration at high L. If particles are locally accelerated to 1 Mev on high L-shells and then move to the heart of the outer zone, separate local acceleration and transport mechanisms are required. Local acceleration mechanisms will be discussed in a later section. Transport mechanisms which conserve a particle's kinetic energy as its mirror point moves to regions of increasing field strength must violate the particle's first adiabatic invariant. Such first invariant diffusion was proposed by Herlofson (1960) as a possible source of the inner and outer zones. This specific mechanism is not considered a probable source of the outer zone because no strong injection source of 1-Mev electrons or protons has been observed on high L-shells.

First invariant diffusion is important, however, because it is involved in several possible injection models. Pitch angle scattering produces first invariant diffusion for two reasons. First, when a particle is randomly scattered, it immediately begins spiralling about a new field line. As a result, the particle's guiding center moves about one cyclotron radius. In addition, shell splitting changes the drift shell followed by a trapped particle each time the particle's mirror point changes.

Specific cases must be investigated to see which effect produces the most rapid first invariant diffusion.

The present study is concerned with roughly 1-Mev electrons and protons. Cyclotron radii of 1-Mev electrons vary between 20 and 50 km in the region between L = 5 and 7, while 1 Mev proton cyclotron radii are 500 to 1500 km. The maximum possible shell splitting produced by pitch angle scattering is about 1500 to 10,000 km in this same region (Roederer, 1967). Since random scattering takes place at arbitrary longitudes and involves arbitrary pitch angle changes, we will use 500 to 3000 km as mean radial displacements owing to shell splitting at L = 5 to 7. Shell splitting is therefore the dominant cause of first invariant diffusion for electrons at least down to L = 5 and probably throughout the outer zone. The two effects are of comparable importance for 1-Mev protons.

After N scattering events the mean radial displacement will be $\sqrt{N}$ times the mean displacement for a single event. The probability of loss per scattering event can be estimated as 1 - cos α where α is given by $\sin^2 \alpha = B_{equator}/B_{earth}$. Using B_{earth} = 0.5 gauss and $B_{equator}$ between 275 and 100 gammas in the range L = 5 to 7, an average particle undergoes between 400 and 1000 random scattering events before striking the earth's atmosphere. These estimates imply that a randomly scattered particle will diffuse radially by 10,000 km before it strikes the dense atmosphere even at L = 5.

We conclude that first invariant diffusion must be an important energy transport mechanism in the outer zone

for any particle lost by random pitch angle scattering. Paolini et al. (1967) have presented experimental evidence that first invariant diffusion is important for 1-Mev electrons in the outer zone.

Acceleration throughout the magnetosphere. Most studies of third invariant diffusion have assumed sudden impulses are the perturbations which drive the diffusion (Parker, 1960; Davis and Chang, 1962; Nakada and Mead, 1965; Tverskoy, 1965). With this driving source, energetic particles move throughout the magnetosphere and time periods of months to years are required to establish equilibrium distributions in the heart of the outer zone.

If the observed rapid changes in electron and proton fluxes are to be produced by third invariant diffusion, a much stronger perturbation than sudden impulses is required. Fluxes of 1-Mev electrons in the heart of the outer zone respond within two hours of the start of a large bay event (Brown et al., 1968) and reach peak values at least within a few days. The entire non-adiabatic process may take place in only a few hours with later flux increases being produced mainly by ring current decay. In the inner zone, however, sudden impulses could be important in driving third invariant diffusion.

Third invariant diffusion from the highest possible trapped orbits down to the heart of the outer zone only involves a change in magnetic field by a factor of 5 to 10 near the equator. Proton acceleration is limited to this

factor, while electron acceleration is even less efficient owing to relativistic effects. Third invariant diffusion of 1-Mev particles into the heart of the outer zone, therefore, requires a source of several-hundred-kev particles on the outermost complete drift shells.

Acceleration beyond the plasmapause. One perturbation which could drive rapid third invariant diffusion is a varying magnetospheric convection system (Axford and Hines, 1961). Freeman (1968) has reported convection velocities of 30 km/sec during bay events. The observed ion flux varied greatly with a period of 10 to 30 minutes in at least one example presented. This provides an ideal situation for rapid third invariant diffusion. The drift periods of 1-Mev electrons and protons near the heart of the outer zone are 10 to 20 minutes. The observed rapid changes in convection flow suggest the Mev particles can be strongly convected toward lower L values on one portion of their orbit and only weakly convected to higher L later on in the same orbit.

The effect of this process can be illustrated by a simple example. Assume a particle with a 15 minute drift period spends a net interval of two minutes in a region of 30 km/sec inward convection. This two minute interval could represent the only portion of the orbit during which convection takes place. Alternatively, the convection velocity could be varying uniformly with time and average 8 km/sec higher when the particle is moving inward than when it is mov-

ing outward. The net result in either case is a radial displacement of 3600 km during a 15 minute orbit. During two hours or 8 orbits, an average particle would therefore diffuse $3600 \sqrt{8} = 10,200$ km. Some particles would move much faster than this average. For example, if the convection system flows at 30 km/sec while the particle is moving toward lower L and stops while the particle drifts through the outward flow region, the average velocity would be 15 km/sec or 8.5 earth radii/hour.

Several-hundred-kev particles produced on the highest trapped orbits should therefore begin arriving at the heart of the outer zone several tens of minutes after a fluctuating convection system begins. This mechanism will not, however, inject particles throughout the magnetosphere. The inner limit of direct injection is the inner limit of the convection system.

Local acceleration within the outer zone. A convection system can transport energy to the heart of the outer zone. This energy must then be transferred to individual charged particles to raise their energies above 1 Mev. Williams et al. (1968) observed that Mev electrons first appear near the equator and are seen near the feet of field lines only after a significant time delay. This suggests that if acceleration is localized to a given drift shell it must also be localized to a region near the equator. As a result, the particle's mirror point field strength cannot increase sig-

nificantly during acceleration. The first adiabatic invariant must therefore be violated. The most likely possibility involves a coherent increase of the energetic particle's transverse velocity owing to cyclotron resonance between the particle and a wave.

If particles are accelerated to 1 Mev deep within the magnetosphere, they will subsequently move inward and outward owing to first and third invariant diffusion.

Sources on high L-shells. Acceleration to 1 Mev owing to third invariant diffusion was seen to require a source of several-hundred-kev particles on the outermost complete drift shells. Regardless of whether or not third invariant diffusion produces the 1 Mev electrons, a "source" of 100-kev particles is observed to be present at L = 8 (Figures 1, 2). Such particles could be produced by the local acceleration mechanism just discussed, by pumping mechanisms, or by injection from very low field regions.

Pumping involves the repeated application of acceleration and redistribution processes. The particle's energy changes during each acceleration phase. Redistribution violates the first adiabatic invariant and prepares the particle for another acceleration phase.

One pumping process that could provide a steady source of energetic particles on high L-shells combines third invariant diffusion for acceleration and first invariant diffusion for redistribution. Particles gain energy as they diffuse

inward by third invariant diffusion. Some then move outward by first invariant diffusion and can undergo a second acceleration phase by third invariant diffusion. For maximum efficiency, this process requires a region of space where the rates of radial displacement by the two diffusion processes are comparable. The previously presented crude estimates of diffusion rates indicate that the two processes are of comparable strength near and beyond L = 6 when a fluctuating convection system is present.

A second pumping process involves Fermi acceleration plus redistribution through pitch angle scattering. Rapid Fermi acceleration is possible within the magnetosphere in a region where hydromagnetic waves are found moving down field lines (Kaufmann, 1963). The waves sweep particles ahead of them, lower their mirror points, and accelerate the particles while conserving the first invariant. Pitch angle scattering near the equator is then required to redistribute mirror points for another acceleration phase.

This process accelerates particles by pumping mirror points up and down field lines rather than in and out across L-shells as in the case of 3rd and 1st invariant diffusion. The Fermi-pitch angle mechanism is most likely to be efficient near the magnetopause where most hydromagnetic waves originate.

Other pumping mechanisms involve the magnetotail. Behannon and Ness (1966) have presented evidence that additional magnetic field lines are carried into the tail during geo-

magnetic storms. Such stretching of field lines into the tail involves deceleration of energetic particles. Energetic particles would be subject to enhanced pitch angle scattering within the tail, particularly near the neutral sheet. Eventually, the field line will return to its original configuration, and the remaining energetic particles will be reaccelerated. Some of the particles which undergo this deceleration, pitch angle scattering, reacceleration cycle will experience a net acceleration.

The third invariant violating mechanisms discussed so far have required two step processes to reach 1 Mev. If a particle is originally trapped in a very low field region, its energy must increase by a large factor as it moves to the heart of the outer zone provided only the third adiabatic invariant is violated. The neutral sheet in the tail is such a very low field region. Speiser and Ness (1967) observe fields varying from 4 gammas to less than 1 gamma in various parts of the neutral sheet. Characteristic dimensions of the neutral sheet range from 500 km to 5000 km. It is, therefore, unlikely that an energetic particle's first invariant can be conserved if the particle's cyclotron radius exceeds 100 km.

Protons with energies as low as 1 kev require a 46 gamma field to produce a 100 km cyclotron radius. We conclude it is not possible to accelerate protons by large factors in a single step by starting from very low field

regions and conserving the first adiabatic invariant.

Electrons with energies of 1 kev and 10 kev require only 1- and 3- gamma fields to produce 100-km cyclotron radii. Conservation of the first invariant requires that an electron starting with 1 kev of energy in a 1-gamma field will reach 200 kev at L = 5 and 600 kev at L = 3. These electrons are not energetic enough to contribute significantly to the observed 1- to 2- Mev flux. A 10-kev electron starting in a 3-gamma field will reach 1.2 Mev at L = 5 and 2.7 Mev at L = 3. These electrons can produce the observed 1- to 2-Mev count rate. To be effective, approximately 10-kev electrons must be trapped so that their mirror points initially lie in a 3-gamma field. The electrons must then be carried to L = 3 to 5 while the first adiabatic invariant is conserved.

4. DISCUSSION

Some of the more important observations presented in Section 2 will now be compared to the models discussed in Section 3.

1. Fluxes of 1- to 2- Mev electrons injected during storms were observed to be strongly peaked and to have a sharp inner boundary. The location of the peak flux is correlated with Dst. This behavior is expected if a convection system is responsible for energy transport during injection. Deep penetration of the convection system results in the in-

jection of energetic particles throughout a large region of the magnetosphere and therefore results in a large decrease in Dst. After injection, the Mev electrons spread owing to first invariant diffusion.

2. The double peaked structures observed in electron radial distributions provide strong evidence that the rapid loss mechanism operating during storms is confined to the region beyond some inner boundary. Pitch angle scattering owing to interactions with spatial inhomogeneities within a convection system is well confined to the region in which the convection system operates. Loss by third invariant diffusion before new source particles are accelerated is also limited to the region containing the convection system. Pitch angle scattering owing to wave interactions, however, will take place wherever waves can propagate. If wave interactions are responsible for the rapid loss of electrons during storms, then the waves must be confined to the region beyond a sharp inner boundary.

3. Assuming 100-kev electrons at L = 8 can be considered a third invariant diffusion source, it was noted that source electrons are present during each injection event. In addition, there seems to be some correlation of the "source" electron flux with the flux of 1- to 2- Mev electrons in the heart of the outer zone. This is most obvious during the September 30 storm when both fluxes are unusually low.

A large flux of "source" electrons was observed during

mid-September with no accompanying injection event. This shows that local acceleration is possible on high L-shells in the absence of an effective energy transport mechanism.

4. Proton fluxes are concentrated near the equator at the heart of the outer zone. This observation implies that either the proton acceleration or transport mechanism must be most efficient in equatorial regions. Second invariant violating mechanisms, such as Fermi acceleration, are therefore unlikely to be important in the heart of the outer zone. Local acceleration involving resonant interactions near the particle's cyclotron period could be important provided the interaction is most efficient near the equator. Third invariant diffusion produced by magnetic field perturbations has also been shown to be most efficient near the equator (Conrath, 1967).

5. It was observed in Figures 1 and 2 that proton fluxes change during each storm, but the details of these changes are masked by orbital effects and by the effects of adiabatic processes. Søraas and Davis (1968) have carefully analyzed similar 100-kev to 1700-kev proton data from Explorer 26. They observe sudden non-adiabatic flux changes in the outer zone during storms. Their 513-kev to 775-kev proton data can be compared to 1-Mev electron data from Explorer 26 (Williams et al., 1968) to see if these two groups of particles with similar drift periods change simultaneously on a given L-shell, as is required if third invariant diffusion

is important. Five storms are studied by Williams et al. Söraas and Davis's data generally show a simultaneous non-adiabatic change in proton flux down to an L-shell which is at or slightly above the peak of the newly injected electron flux. This implies that third invariant diffusion can produce the observed electron flux changes only down to the peak of the electron radial distribution. Below this point, first invariant diffusion can produce the observed electron flux changes, as suggested by Paiolini et al. (1967). First invariant diffusion will also alter the electron fluxes on higher L-shells, so that electrons in the heart of the outer zone will spread to both higher and lower altitudes. Protons do not undergo rapid pitch angle scattering below L = 5 to 6 and therefore do not undergo rapid first invariant diffusion in this region. As a result, third invariant diffusion can dominate proton flux changes down to lower altitudes.

These observations suggest that protons are easier to treat theoretically than electrons in this energy range. To study third invariant diffusion, it would be better to use data taken shortly after a large storm rather than the equilibrium radial distributions which are sensitive to loss mechanisms and first invariant diffusion. If a convection system drives the third invariant diffusion, then the diffusion coefficient cannot be proportional to L^{-n} down to the earth's surface, but must decrease sharply at a much higher altitude. The most important drawback in using proton data is that very

large corrections must be applied to "correct" for B/B_o, Dst, and other effects. The long proton lifetime also implies that the distribution seen at any particular time will be the result of a number of injection events, except possibly immediately after a very large storm.

Electrons are easier to study experimentally because they are less sensitive to "corrections" for orbital effects and because electron fluxes decay so rapidly that new injection events are prominent. These effects plus the presence of rapid first invariant diffusion make electrons more difficult to study theoretically except perhaps immediately after a large storm.

ACKNOWLEDGEMENTS

We wish to express our appreciation to L. R. Davis for the use of the Explorer 12 ion and electron detector data. This work was supported in part by the Atmospheric Sciences Section, NSF Grants GP-5255 and GA-1131.

REFERENCES

Axford, W. I., and C. O. Hines, A unifying theory of high-latitude geophysical phenomena and geomagnetic storms, Can. J. Phys., 39, 1433, 1961.

Behannon, K. W., and N. F. Ness, Magnetic storms in the earth's magnetic tail, J. Geophys. Res., 71, 2327, 1966.

Conrath, B. J., Radial diffusion of trapped particles with arbitrary pitch angle, J. Geophys. Res., 72, 6069, 1967.

Daniels, W. E., Jr., GLSWS - General least squares with statistics, University of Maryland Technical report number 579, 1966.

Davis, L., Jr., and D. B. Chang, On the effect of geomagnetic fluctuations on trapped particles, J. Geophys. Res., 67, 2169, 1962.

Davis, L. R., and J. M. Williamson, Low energy trapped protons, Space Res., [illegible], 365, 1963.

Frank, L. A., R. C. Bohlin, and R. J. DeCoster, Graphic summary of the responses of the University of Iowa charged particle detectors on Explorer 12, University of Iowa Report 66-15, 1966.

Freeman, J. W., Jr., Observations of flow of low-energy ions at synchronous altitude and implications for magnetospheric convection, J. Geophys. Res., 73, 4151, 1968.

Herlofson, N., Diffusion of particles in the earth's radiation belts, Phys. Rev. Letters, 5, 414, 1960.

Jensen, D. C., and J. C. Cain, An interim geomagnetic field (abstract), J. Geophys. Res., 67, 3568, 1962.

Kaufmann, R. L., Experimental tests for the acceleration of trapped particles, J. Geophys. Res., 68, 371, 1963.

Kellogg, P. J., Van Allen radiation of solar origin, Nature, 183, 1295, 1959.

McIlwain, Processes acting upon outer zone electrons 1. Adiabatic perturbations, Presented at Interunion Symposium on Solar-Terrestrial Physics, Belgrade, Yugoslavia, 1966.

Nakada, M. P., and G. D. Mead, Diffusion of protons in the outer radiation belt, J. Geophys. Res., 70, 4777, 1965.

Owens, H. D., and L. A. Frank, Electron omnidirectional intensity contours in the earth's outer radiation zone at the magnetic equator, J. Geophys. Res., 73, 199, 1968.

Paolini, F. R., G. C. Theodoridis, and S. Frankenthal, Space and time variations in outer-belt electron spectra, J. Geophys. Res., 72, 4590, 1967.

Parker, E. N., Geomagnetic fluctuations and the form of the outer zone of the Van Allen radiation belt, J. Geophys. Res., 65, 3117, 1960.

Roederer, J. G., On the adiabatic motion of energetic particles in a model magnetosphere, J. Geophys. Res., 72, 981, 1967.

Soraas, F., and L. R. Davis, Temporal variations of the 100 kev to 1700 kev trapped protons observed on satellite Explorer 26 during first half of 1965, Goddard Report, X-612-68-328, 1968.

Speiser, T. W., and N. F. Ness, The neutral sheet in the geomagnetic tail: Its motion, equivalent currents, and field line connection through it, J. Geophys. Res., 72, 131, 1967.

Tverskoy, B. A., Transport and acceleration of charged particles in the earth's magnetosphere, Geomag. and Aero., 5, 617, 1965.

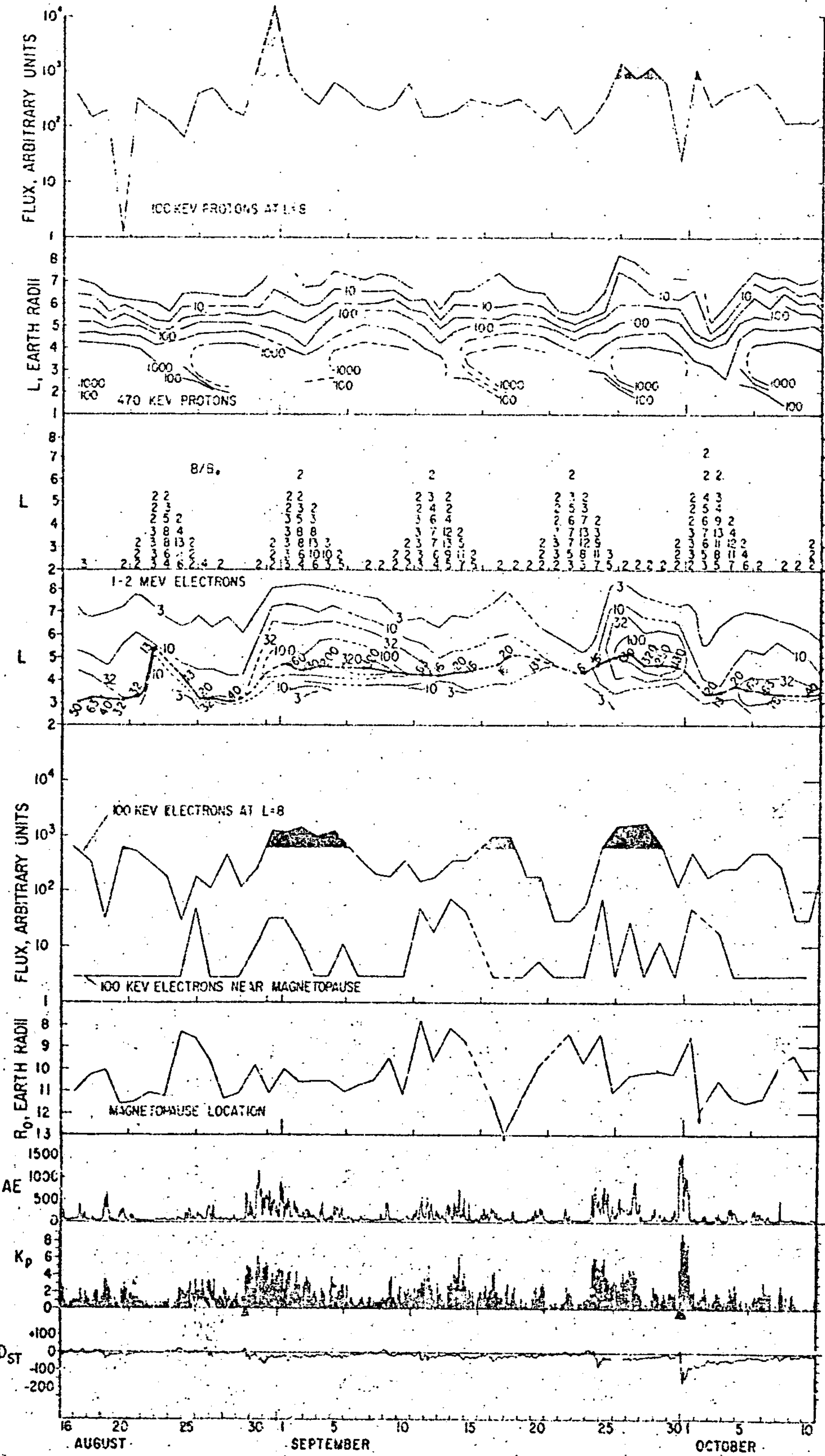
Williams, D. J., J. F. Arens, and L. J. Lanzerotti, Observations of trapped electrons at low and high altitudes, J. Geophys. Res., 73, 5673, 1968.

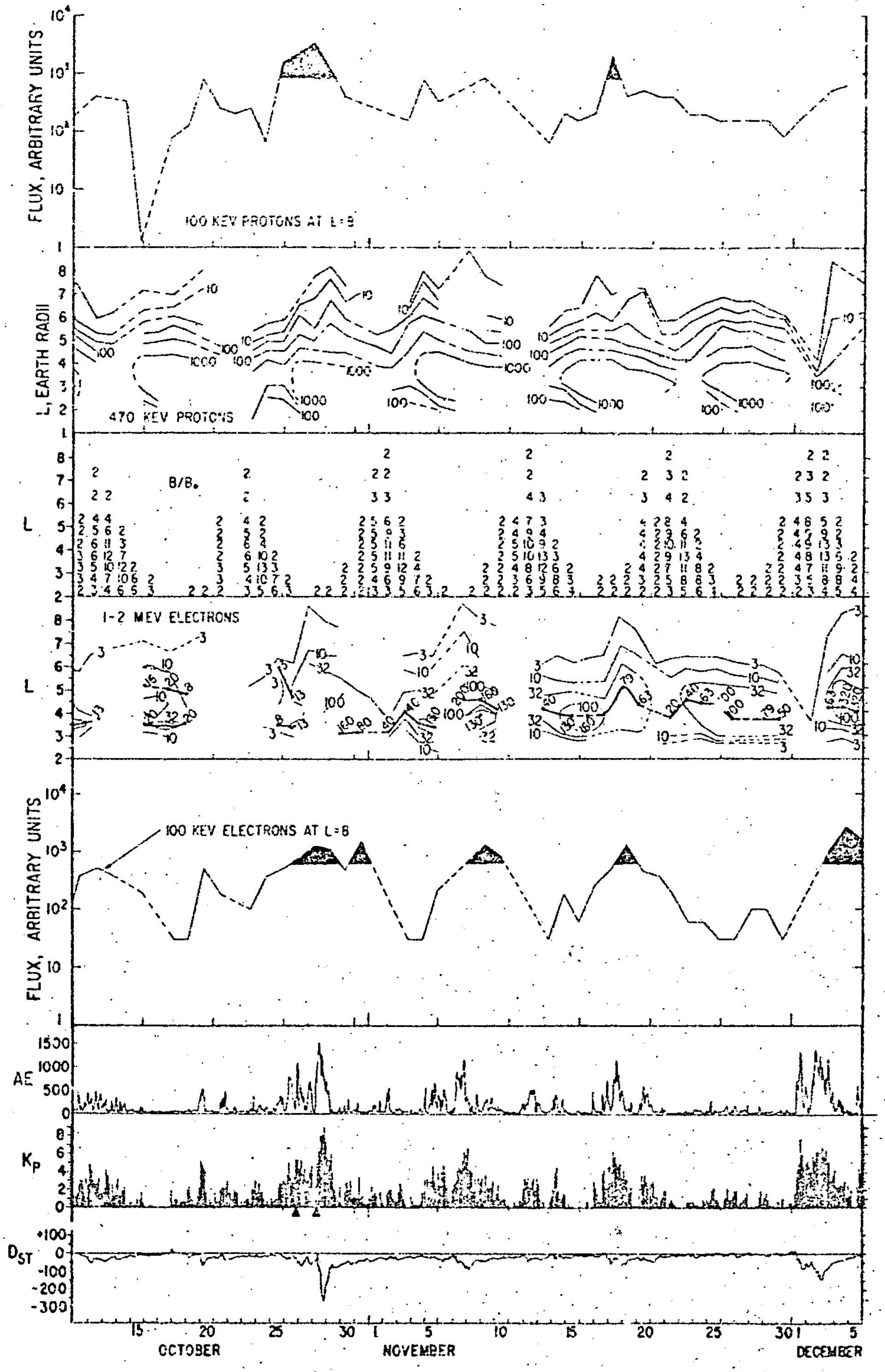
Wong, Y. S., C. Echols, and T. N. DAvis, Hourly values of the auroral electrojet activity index AE for 1961, University of Alaska Report UAG R-196, 1967.

FIGURE CAPTIONS

Figure 1. Fluxes of electrons and protons with energies above about 100 kev at L = 8 are compared with contour plots of more energetic electrons and protons throughout the outer zone. The 100-kev electron flux near the magnetopause, the magnetopause location, and several geomagnetic indices are also shown. The curves are explained in more detail in the text.

Figure 2. Continuation of Figure 1.


FLUX, ARBITRARY UNITS
100 KEV PROTONS AT L=8
L, EARTH RADII
470 KEV PROTONS
L
1-2 MEV ELECTRONS
100 KEV ELECTRONS AT L=8
100 KEV ELECTRONS NEAR MAGNETOPAUSE
R_0, EARTH RADII
MAGNETOPAUSE LOCATION
AE
K_p
D_{ST}
AUGUST
SEPTEMBER
OCTOBER



FLUX, ARBITRARY UNITS
100 KEV PROTONS AT L=8
L, EARTH RADII
470 KEV PROTONS
B/B₀
1-2 MEV ELECTRONS
100 KEV ELECTRONS AT L=8
AE
Kp
DST
OCTOBER
NOVEMBER
DECEMBER